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A NEW THREE-SALT NUTRIENT SOLUTION FOR PLANT CULTURES

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The majority of the nutrient solutions hitherto employed in the study of the salt nutrition of plants have contained four or more principal salts, besides the trace of a salt of iron, but the 36 different solutions used by Shive¹ differ from the earlier ones in the fact that they all contain the six essential ions (besides iron) in the form of only three salts. These essential ions are: Ca, K, Mg, NO₃, SO₄ and PO₄, and Shive put them into the solution in the form of the three salts, calcium nitrate (Ca(NO₃)₂), magnesium sulphate (MgSO₄), and mono-potassium phosphate (KH₂PO₄). It is at once suggested that the six requisite ions might enter into the solution as other salts than the three just mentioned, and the question arises whether or not a suitable solution for the growth of plants might not be made with one of the five other possible combinations.

The six logically possible ways by which these six essential ions may enter into the solution, always employing just three salts, are indicated by the following scheme; they are numbered serially, by Roman numerals.

I	II	III	IV	V	VI
Ca(NO ₃) ₂ KH ₂ PO ₄ MgSO ₄	Ca(NO ₃) ₂ K ₂ SO ₄ Mg(H ₂ PO ₄) ₂	Ca(H ₂ PO ₄) ₂ KNO ₃ MgSO ₄	Ca(H ₂ PO ₄) ₂ K ₂ SO ₄ Mg(NO ₃) ₂	CaSO ₄ KNO ₃ Mg(H ₂ PO ₄) ₂	CaSO ₄ KH ₂ PO ₄ Mg(NO ₃) ₂

Before an adequate discussion of the salt nutritional requirements

¹ Shive, J. W. A study of physiological balance in nutrient media. *Physiol. Res.* 1: 327-397. 1915. A preliminary announcement appeared as: A three-salt nutrient solution for plants. *Amer. Journ. Bot.* 2: 157-160. 1915.

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of any kind of plant may be possible, all six of these salt combinations must of course be thoroughly tested with reference to the plant in question. Hitherto, only the first of these has received attention in the literature, the salts of group I being those employed in Shive's elaborate study. The present paper shows the results of a preliminary test of a series of solutions using group III—potassium nitrate (KNO_3), magnesium sulphate (MgSO_4), and mono-calcium phosphate ($\text{Ca}(\text{H}_2\text{PO}_4)_2$).

In order to investigate in an adequate way the combination of these three salts in plant cultures, it is of course necessary to include a number of different sets of salt proportions and a number of total concentrations or osmotic values, as both Tottingham² and Shive have pointed out. Shive tested thirty-six different sets of salt proportions and three different total osmotic values, so that he dealt with 108 different solutions, all made with the same three salts. The preliminary study here reported involved, however, only one total concentration, about the same as the one termed *optimal* by Shive (osmotic value about 1.75 atmospheres), and only twelve sets of salt proportions were here employed. These were selected to correspond to certain ones of Shive's thirty-six, rather evenly distributed over his triangular diagram.

In preparing the solutions, it was assumed as approximately correct that the osmotic effect of dissociation occurring in these solutions is the same for $\text{Ca}(\text{H}_2\text{PO}_4)_2$ as it was taken to be for $\text{Ca}(\text{NO}_3)_2$ in Shive's work. Likewise, it was assumed that the osmotic effect of the dissociation of KNO_3 in these solutions is approximately like that calculated for KH_2PO_4 by Shive. Finally, it was assumed that the osmotic effect of the dissociation of MgSO_4 is the same in our solutions as it was taken to be in Shive's calculations for the same salt. Following these assumptions, the partial volume-molecular concentrations of our salts are the same as those for the corresponding sets of salt proportions shown in Shive's table for the total concentration value of 1.75 atmospheres, but of course we employ $\text{Ca}(\text{H}_2\text{PO}_4)_2$ instead of Shive's $\text{Ca}(\text{NO}_3)_2$, and KNO_3 instead of his KH_2PO_4 . Using Shive's designations for the different solutions (referring to his triangular diagram), the partial volume-molecular concentrations of each of our three salts, in each of our 12 solutions, are given in table I.

² Tottingham, W. E. A quantitative chemical and physiological study of nutrient solutions for plant cultures. *Physiol Res.* 1: 133-245. 1914.

TABLE I

Partial volume-molecular concentrations of each of the three salts used, for twelve different sets of salt proportions, the solution numbers corresponding to those employed by Shive. Total osmotic value about 1.75 atmospheres in every case.

Solution No.	Partial Volume-molecular Concentration		
	KNO ₃	Ca(H ₂ PO ₄) ₂	MgSO ₄
R1C1.....	.0036	.0026	.0400
C3.....	.0036	.0078	.0300
C6.....	.0036	.0156	.0150
C8.....	.0036	.0308	.0050
R2C4.....	.0072	.0104	.0200
R3C1.....	.0108	.0026	.0300
C6.....	.0108	.0156	.0050
R4C2.....	.0144	.0052	.0200
C4.....	.0144	.0104	.0100
R6C1.....	.0216	.0026	.0150
C3.....	.0216	.0078	.0050
R8C1.....	.0288	.0026	.0050

It was found that all these solutions could be made up from stock solutions of the individual salts, without the formation of precipitate, and that they were stable. Ferric phosphate was added to each culture jar, in the manner followed by Shive.

Wheat of the same variety as was used by Shive ("Fulcaster") was here employed, and the general technique was the same throughout as in his experimentation. Our culture period extended from May 15 to June 2, 1917, thus embracing 18 days. The cultures stood on a rotating table in the same greenhouse as was used by Shive. For the period in question the absolute minimum temperature was 13° C. and the average of the daily minima was 18° C.; the absolute maximum temperature was 39° C. and the average of the daily maxima was 30° C. The corrected water loss from a Livingston standard white spherical porous-cup atmometer was 295 cc. for the period, giving an average rate of 16.4 cc. per day.

Besides the twelve cultures employing the new solutions, our series also included three like cultures with Shive's best solution for wheat, introduced for comparison. This is his solution R5C2 (optimal concentration), containing the following three salts in the partial volume-molecular proportions indicated: KH₂PO₄, 0.0180; Ca(NO₃)₂, 0.0052; MgSO₄, 0.0150.

The total amount of solution removed from each jar by the six plants during the entire period (which is practically the same as the

amount of water transpired) was determined, as were also the approximate average length of main roots, the dry yield of tops and the dry yield of roots. The sum of top and root yields is of course the total yield.

These data are presented in table 2, which shows the actual values for the three similar Shive solutions, and their average, in each case, and also the *relative* values for each of the twelve new solutions. The relative values have been calculated on the basis of the corresponding average from the Shive solutions, this average considered as unity. Thus, each datum is expressed in terms of the corresponding average from the triplicate Shive solution, and the several data from the new solutions are directly comparable throughout each separate column of the table. The highest value in each column is denoted by bold-face type.

TABLE 2

Water absorbed, average root length and dry yields of tops, of roots, and of entire plants, for wheat grown 18 days in the solutions characterized in table 1, each value expressed in terms of the average of the three corresponding values obtained from Shive's best solution for wheat (controls 1, 2, and 3).

Solution No.	Water Absorbed	Mean Root Length	Dry Yield		
			Tops	Roots	Entire Plants
Control 1	247 cc.	24.6 cm.	.491 g.	.153 g.	.644 g.
" 2	240 cc.	25.1 cm.	.474 g.	.152 g.	.626 g.
" 3	253 cc.	23.5 cm.	.509 g.*	.175 g.	.684 g.
Control average	247 cc. (1.00)	24.4 cm. (1.00)	.491 g. (1.00)	.160 g. (1.00)	.651 g. (1.00)
R1C1 . . . . .	.85	.53	.79†	.92	.82
C3 . . . . .	.83	.50	1.05*	.95	1.03
C6 . . . . .	.57	.28	.70§	.66	.69
C8 . . . . .	.35	.29	.45§	.50	.46
R2C4 . . . . .	.92	.44	.97†	.83	.94
R3C1 . . . . .	.92	.80	.84†	.99	.88
C6 . . . . .	.48	.30	.58§	.61	.59
R4C2 . . . . .	.97	.66	.95*	.94	.95
C4 . . . . .	.85	.41	.85§	.86	.85
R6C1	1.07	1.00	1.02†	1.14	1.05
C3	1.04	.60	.95†	.98	.96
R8C1	1.10	.94	1.02	1.10	1.04

* Slight magnesium injury.

† Severe magnesium injury.

‡ Slight acid injury.

§ Severe acid injury.

The data of table 2 lead to the conclusion that solution R6C1 is

physiologically the most efficient on the basis of the whole group of criteria employed. Of course this is not to be interpreted to mean that this solution is the very best possible for this plant, for these climatic conditions and for these criteria, since the distribution of our solutions on the triangular diagram is rather open, much more so than in the case of Shive's series of thirty-six different sets of salt proportions, and of course some other set of proportions than those here tested might have given still higher plant values. It is not probable, however, that either the growth values or the salt proportions of such a hypothetical very best solution might have been pronouncedly different from those indicated.

On the triangular diagram, this solution of our series lies very close to Shive's best solution for wheat; ours is R6C1, while his is R5C2, and solution R5C2 was not tested in our series.

The relative data show that our single culture with solution R6C1 gave somewhat higher values than the corresponding average of the three controls with Shive's best solution, in all cases excepting that of root length. The approximate mean length of the main roots for our solution R6C1 is shown to be equal to the control average. The variations due to unknown conditions ("individual variations") are always so great in this sort of experimentation, however, that no particular emphasis should be placed upon the indications that our solution R6C1 gave better growth than did Shive's best; for it is to be remembered that the data for our twelve new solutions are derived from single cultures, of only six plants each. For the present, it is sufficient to say that our three-salt solution R6C1 is apparently *just as good* for the growth of young wheat plants (judged by the numerical data of table 2) as is Shive's optimal R5C2, despite the fact that the proportions of the component ions are considerably different in the two solutions.

It does not seem desirable to enter into further discussion of these results at the present time, on account of the paucity of our data, but it may be of value to present briefly our observations on the apparent health of the plants in the various solutions. The peculiar morphological responses called "magnesium injury" by Tottingham, which frequently occur with Shive's optimal R5C2 for wheat, appeared in some of the cultures (see the asterisks in the fourth column of table 2), and they were pronounced with solution R6C1, the one that appears best on the basis of the numerical values. In this set they occurred

in but one of the three controls. It appears that some evidences of poisoning may be expected whenever maximum dry-weight values are obtained with young wheat plants,³ if the transpiration rate is not too low. Our best culture *without magnesium poisoning* was with solution R8C1, and this solution appears to be about as efficient as R6C1 on the basis of the growth data of table 2. As might be expected, the greatest water-absorption (transpiration) occurred with solution R8C1, where leaf injury was not manifest, but the difference between R8C1 and R6C1 is not great. In regard to the dry yield of tops, solutions R6C1 and R8C1 appear to be equivalent from the rounded-up data of the table, but there is actually a slight (though insignificant) difference between them, in favor of the former.

Another form of injury, consisting of a withering and darkening of the leaf backward from the tip, occurred in certain cultures that were free from magnesium injury (see those marked ‡ and § in the fourth column of table 2). It is suggested that this is due to too high acidity of the solution, and it may be tentatively called "acid" injury, until the relations of hydrogen-ion concentration are studied in such series as these. No acid injury was manifest with either solution R6C1 or R8C1, nor was it observed in any of the controls.

Summarizing the results of this preliminary study, it appears that the numerical criteria that we employed indicate that our solution R6C1 is as good as (or slightly better than) Shive's optimal solution R5C2. Both these solutions induce some magnesium injury in young wheat plants, however. Considering the occurrence of this injury and the criterion of water absorption, as well as the production of dry yield, the best balanced solution (for these plants) of our entire series is R8C1, which contains, per liter, 0.0288 g.-mol. of KNO_3 , 0.0026 g.-mol. of $\text{Ca}(\text{H}_2\text{PO}_4)_2$, and 0.0050 g.-mol. of MgSO_4 . This solution appears to be better suited to give maximum growth combined with perfect health of plants than does either one of the two other solutions just mentioned. Judging from all the evidence at hand (including

³ This point was first emphasized by Free and Trelease, who remark: "It may be a general rule that increased growth is the first response to agents or circumstances which would prove injuriously toxic in greater concentration or on longer exposure. . . . In other words, slight poisoning, such as that caused by magnesium or boron, is essential for the production of the greatest dry weight of tops. Either magnesium or boron will serve." See: Free, E. E., and Trelease, S. F. The effects of certain mineral poisons on young wheat plants in three-salt nutrient solutions. Johns Hopkins Univ. Circ. March, 1917, pp. 199-201.

various points brought out in Shive's paper), it appears that our solution R8C1 is physiologically the best balanced for young wheat plants of all the nutrient solutions so far noted in the literature, but this matter assuredly requires still further study.

Of course the proportions of the various atoms and atomic groups (constituting the essential ions) are, in our solutions, very markedly different from the corresponding proportions in Shive's series, and table 3 is here appended to emphasize this aspect of the general problem of the salt nutrition of plants and to put the comparative data thus far available in convenient form for future reference. In this table the solutions are each indicated by the proper Roman numeral (referring to the foregoing scheme of six logically possible series of three-salt solutions) and by the symbol showing the position of the particular set of salt proportions considered, on the triangular diagram employed by Shive. This will furnish a convenient method for future reference to the large number (216) of different solutions that will require attention in this field. All three solutions here considered have approximately the same osmotic value (or total concentration), this value being that employed by Shive for his optimum series (1.75 atm.). The index of total concentration should be most conveniently expressed in terms of the lowering of the freezing-point (the familiar Δ of physical chemistry), but the requisite determinations for a statement of these magnitudes are not yet available. In table 3, solution IR5C2 is Shive's optimal R5C2, while solutions IIIR6C1 and IIIR8C1 are the two new well-balanced solutions brought forward in the present paper.

The first column of table 3 shows the various atoms or atomic groups (ions, whether still in their molecules or free in the solution) with which a physiological discussion of these solutions will eventually have to deal. The third column shows the absolute values of the respective partial concentrations, on the basis of solution volume. These may be called the partial volume-ionic or volume-atomic concentrations, but a new term will be required when the dissociated ions are to be considered separately from those still held in the molecules. To illustrate the significance of these values, the quantity 0.0180 in this column (referring to K) denotes that solution IR5C2 contains 18 thousandths of a gram-atom of potassium in a liter of solution. The same quantity occurs below with reference to H_2PO_4 and also to PO_4 , which means that the solution in question contains 18 thousandths of a gram-ion of H_2PO_4 and of PO_4 per liter of solution, the term gram-

ion being used in a sense exactly analogous to that commonly attributed to the corresponding term gram-molecule. It will be noted that the partial volume-atomic concentration value for H is, in this same solution, twice as great as that for K, H_2PO_4 , and PO_4 , which should be clear from the formula of the salt referred to, KH_2PO_4 . The introduction of S and N at the bottom of table 3 does not refer to the existence of such atoms as ions in the solutions, but has reference only to the relative numbers of these atoms present. That these two elements be considered separately in a full description of a nutrient solution seems highly advisable; first, because they are frequently so considered in the literature of nutrient solutions, soil analyses, etc., and second, because it seems highly probable that the supply of these elements to the plant may frequently be important, aside from the particular combinations (compounds or atomic groups) in which they may be supplied. It may be once more emphasized that the use of weight percentages (parts per million, etc.) to designate the partial concentration characteristics of solutions and soils ought to be discontinued in this sort of study, since such terminology is not only meaningless in any thoroughgoing physiological or chemical discussion, but is actually misleading to many readers and clouds the very important issues involved.

The fourth column of table 3 presents the respective values of the third column in relative form, the value given for K in the second column (for the solution R5C2) being here taken as unity throughout. These values thus represent the numbers of the respective atoms, etc., present in each solution, per unit of volume, in terms of the number of potassium atoms in solution IR5C2. It appears, for example, that solution IR5C2 contains 2.89 times as many calcium atoms as it does potassium atoms, per volume unit. The values of the last column of table 3 are likewise relative, but here the partial volume-atomic (or volume-ionic) concentration of the ion or atomic group in question, in solution IR5C2, is taken as unity. As an illustration, it is apparent that there are only half as many atoms of calcium, per unit of volume, in solution IIIR6C1 as there are in solution IR5C2.

The data of table 3 make it clear how very different are the atomic and ionic proportions in Shive's solution IR5C2 and in our best solution, IIIR8C1. The latter can supply to the plant much more potassium and very much more of the nitrate ion than can the former; on the other hand, the supplies of calcium, magnesium, sulphate, and phos-

TABLE 3

Partial volume concentrations of the various atoms and atomic groups (ions) in the three nutrient solutions, IR₅C₂, IIR₆C₁, and IIR₈C₁, all three having an osmotic value of about 1.75 atmospheres.

Ion (or Atom)	Solution	Partial Vol.-ionic (or Vol.-atomic) Concentration*		
		Absolute	Relative to	
			K of Same Solution	Same Ion, Etc., of IR ₅ C ₂
K.....	IR ₅ C ₂	.0180	.100	1.00
	IIR ₆ C ₁	.0216	.100	1.20
	IIR ₈ C ₁	.0288	.100	1.60
Ca.....	IR ₅ C ₂	.0052	.289	1.00
	IIR ₆ C ₁	.0026	.120	0.50
	IIR ₈ C ₁	.0026	.903	0.50
Mg.....	IR ₅ C ₂	.0150	.833	1.00
	IIR ₆ C ₁	.0150	.694	1.00
	IIR ₈ C ₁	.0050	.174	0.33
SO ₄	IR ₅ C ₂	.0150	.833	1.00
	IIR ₆ C ₁	.0150	.694	1.00
	IIR ₈ C ₁	.0050	.174	0.33
H ₂ PO ₄	IR ₅ C ₂	.0180	.100	1.00
	IIR ₆ C ₁	.0052	.240	2.89
	IIR ₈ C ₁	.0052	.180	2.89
NO ₃	IR ₅ C ₂	.0104	.578	1.00
	IIR ₆ C ₁	.0216	.100	2.08
	IIR ₈ C ₁	.0288	.100	2.77
PO ₄	IR ₅ C ₂	.0180	.100	1.00
	IIR ₆ C ₁	.0052	.216	2.89
	IIR ₈ C ₁	.0052	.180	2.89
H.....	IR ₅ C ₂	.0360	.200	1.00
	IIR ₆ C ₁	.0104	.481	2.88
	IIR ₈ C ₁	.0104	.361	2.88
S.....	IR ₅ C ₂	.0150	.833	1.00
	IIR ₆ C ₁	.0150	.694	1.00
	IIR ₈ C ₁	.0050	.174	0.33
N.....	IR ₅ C ₂	.0104	.578	1.00
	IIR ₆ C ₁	.0216	.100	2.08
	IIR ₈ C ₁	.0288	.100	2.77

* This refers to the atomic group or atom, whether actually separated from the molecule or not; degree of actual ionization is not here considered.

phate are in every case much lower in our best solution than they are in Shive's. Nevertheless, both solutions are excellent for the growth of young wheat plants. As our quantitative and critical knowledge of the relations between nutrient solutions and plant growth is increased, it becomes more and more strongly suggested that it is not atomic, nor

yet ionic nor even molecular, proportions that determine the physiological properties of a solution. The problem thus emphasized is as important in agricultural practice as it is complicated and difficult. The work of many investigators will be required in this field before any serious discussion of the salt-nutrition of plants may even be attempted. It is to be hoped that the results of such work may be allowed to appear as the work goes on, so that our general appreciation of this exceedingly fundamental problem in agricultural science may begin to assume definite form as soon as possible. Thus only can enormous waste of time and human energy, due to our lack of appreciation of these matters, be avoided.

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